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NICKEL-CADIUM AIRCRAFT BATTERIES:
MANAGEMENT FOR ENGINE CRANKING

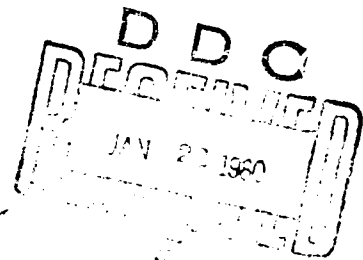by

K. Feldman and G. Verville

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OCTOBER 1979
OTTAWA

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NICKEL-CADMIUM AIRCRAFT BATTERIES:
MANAGEMENT FOR ENGINE CRANKING

by

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ABSTRACT

Nickel/cadmium aircraft batteries with Celgard barrier materials may be freely used for cranking turbine engines. However, frequent use for this purpose with insufficient intervening cooling still results in successive increases in battery temperature. The experiments were terminated when "hot spot" temperatures between the cells reached 100°C. Short term experiments indicated no apparent problems.

In long term use for cranking, performance was found to deteriorate as water depletion, due to overcharge, became severe. Replacement of water and deep cycling restored the original condition.

Improved cranking performance was found with initial electrolyte concentrations below the customary 30% potassium hydroxide.

It is emphasized that the above comments do not apply to batteries with cellophane barriers.

RÉSUMÉ

Les nouveaux accumulateurs au nickel/cadmium munis d'une membrane Celgard comme élément séparateur peuvent être couramment employés pour les démarrages des turbines d'avion. Neanmoins une sollicitation répétée des accumulateurs dans un intervalle de temps court provoque une augmentation continue de la température. Les essais ont été arrêtés lorsque la température mesurée entre deux éléments attaignait 100°C. Les essais à court-terme n'ont révélé aucun problème majeur.

Les performances des accumulateurs se détériorent progressivement à mesure qu'ils perdent leur eau lors des périodes de surcharge. Le remplacement de l'eau perdue accompagné de profonds cyclages redonne les performances originales.

Des performances supérieures ont été réalisées avec des accumulateurs remplis d'électrolytes dont la concentration en potasse était inférieure à 30%.

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INTRODUCTION

The use of Celgard* or other high temperature barrier materials to replace cellophane (1) in nickel/cadmium aircraft batteries has made their widespread use for turbine engine cranking feasible. Consequently, there is a need to review battery management with the application in mind. Questions arise as to whether previously known problems will become more serious or less serious, whether new problems will arise, what criteria should be used in determining the frequency of maintenance periods, whether different maintenance procedures are required, etc. This paper presents the results of an investigation undertaken to explore such areas.

In order to assure the general applicability of the observations, a number of different batteries, some new and some old, were used (see Appendix I). Most of the batteries were of the 22 Ah size. However, a limited amount of work was done with 36 Ah batteries (see Appendix II). Also one of the 22 Ah batteries included cells with Permion and cells with "large pore" Celgard 3500 (see Appendix III).

TEST PROCEDURES

Preliminary work led to the conclusion that a major portion of the investigation would need to be centered on water depletion effects. "Head room" for electrolyte is frequently minimal, gas entrapment may further reduce the volume available, and past experience indicates that very low electrolyte levels frequently occur in the field. Procedures were therefore developed to investigate the interactions between high rate discharges and water depletion. Modifications to the tests were then made as needed.

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* "Celgard" is a family of polypropylene microporous polymeric films developed by the Celanese Plastics Company, Summit, New Jersey, U.S.A.

Batteries were prepared by adjusting the electrolyte concentration and level to the desired values*, and by deep cycling. Characterizing tests (2) were carried out to determine the state of health of each cell. Thermocouples were inserted at various locations between the cells.

The prepared battery was charged at room temperature (22°C-28°C) and allowed to stand on open circuit until the following day. It was then placed in a temperature chamber and "temperature soaked" as necessary.

Starting on the following morning, a 24 minute 10A discharge was carried out to simulate an aircraft check-out procedure. This was followed by two 10 second high rate discharges separated by one minute on open circuit. During this interval, a vacuum was usually applied to the cell vents. By comparing the performances during the two high rate discharges, it was possible to determine the effects of gas entrapment, if any.

Following the second high rate discharge the battery was recharged in the chamber ambient, at a fixed voltage of 1.5 volts per cell with a maximum current limit of 80A. The recharge was usually permitted to continue for approximately 1½ hours.

In the afternoon the above discharges and recharge were repeated again.

The high rate discharges were carried out by applying a 20 milliohm load. For analytical purposes this was considered preferable to simulating an actual engine cranking profile. Also, again to facilitate analysis, the same load and recharge potentials were used for all batteries and temperatures.

After the day's procedures as described above, the battery was removed from the chamber and allowed to reach room temperature. Then, to accelerate the tests, a constant current charge at 10A was carried out for three hours of overcharge to deplete the water in the electrolyte by 10 ml per cell. After an overnight stand on open circuit, the battery was replaced in the temperature chamber and the test cycle was repeated again.

Such sequences were continued until performance deteriorated significantly.

During the tests battery voltage, current, and the individual voltages of four cells were recorded on chart recorders for detailed analyses. Temperature and all cell voltages in the battery were also periodically recorded on data loggers.

After the last run in each series, the battery was given assessment tests and then was reconditioned for the next series.

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* Initially each cell was weighed as a means to accurately determine amounts of water depletion during the experiments. During the early work, however, it was found that (except for cells with cellophane) sufficiently accurate determinations could be made by calculation based on ampere hours of overcharge. Weighing was therefore discontinued.

WATER DEPLETION AND CRANKING PERFORMANCE

In preparation for these tests the electrolyte was always brought to a standard initial level in each cell. In the 22 Ah batteries this level was selected to be 3.6 cm below the top vent cap seat of the cell. The adjustment was always made while continuing to charge the fully charged battery at a rate of 5A.

During the tests it was observed that in all of the 22 Ah batteries, regardless of other details, the peak current into the fixed load always decreased gradually as water was depleted beyond about 10 ml from the above level. Depletion beyond 30 ml resulted in a very rapid fall in performance.

Typical results are given in Figure 1, where the peak current obtained at room temperature is shown for the first high rate discharge each day. Since turbine cranking gives a current profile which starts with a peak value for a few seconds and then decreases rapidly, the battery performance obtained in these tests should parallel that expected in actual cranking.

The results obtained with the four 22 Ah batteries are shown in Figure 2. It is seen that there are significant differences between the peak currents given by the various batteries, depending mostly on their internal resistance. However, the deterioration in performance as water is depleted, is similar in all of them, and might be expected to apply generally, except in cells with significantly more head room for electrolyte.

Analysis of the measurements made during the cranking tests readily shows the mechanism involved in the performance deterioration as water is depleted. Three curves are shown in Figure 3 to illustrate this conclusion. The curves show the current, open circuit voltage and the resistance of battery (a), each plotted versus the amount of water depletion. It is obvious that the small changes in voltage have only a small effect on the current. However, the battery resistance* changes by approximately 17% and, when the load resistance is considered, this change is of the correct order of magnitude to explain the 10% change in current between the 10 ml and 30 ml points of water depletion. Thus the significant factor in reducing cranking performance as water is depleted is the increase in battery resistance.

Presumably several factors participate in the resistance increase. In some circumstances the resistivity of the electrolyte may increase as a result of the change in concentration as water is depleted. In some regions

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* Calculated from instantaneous ΔV and ΔI values (3).
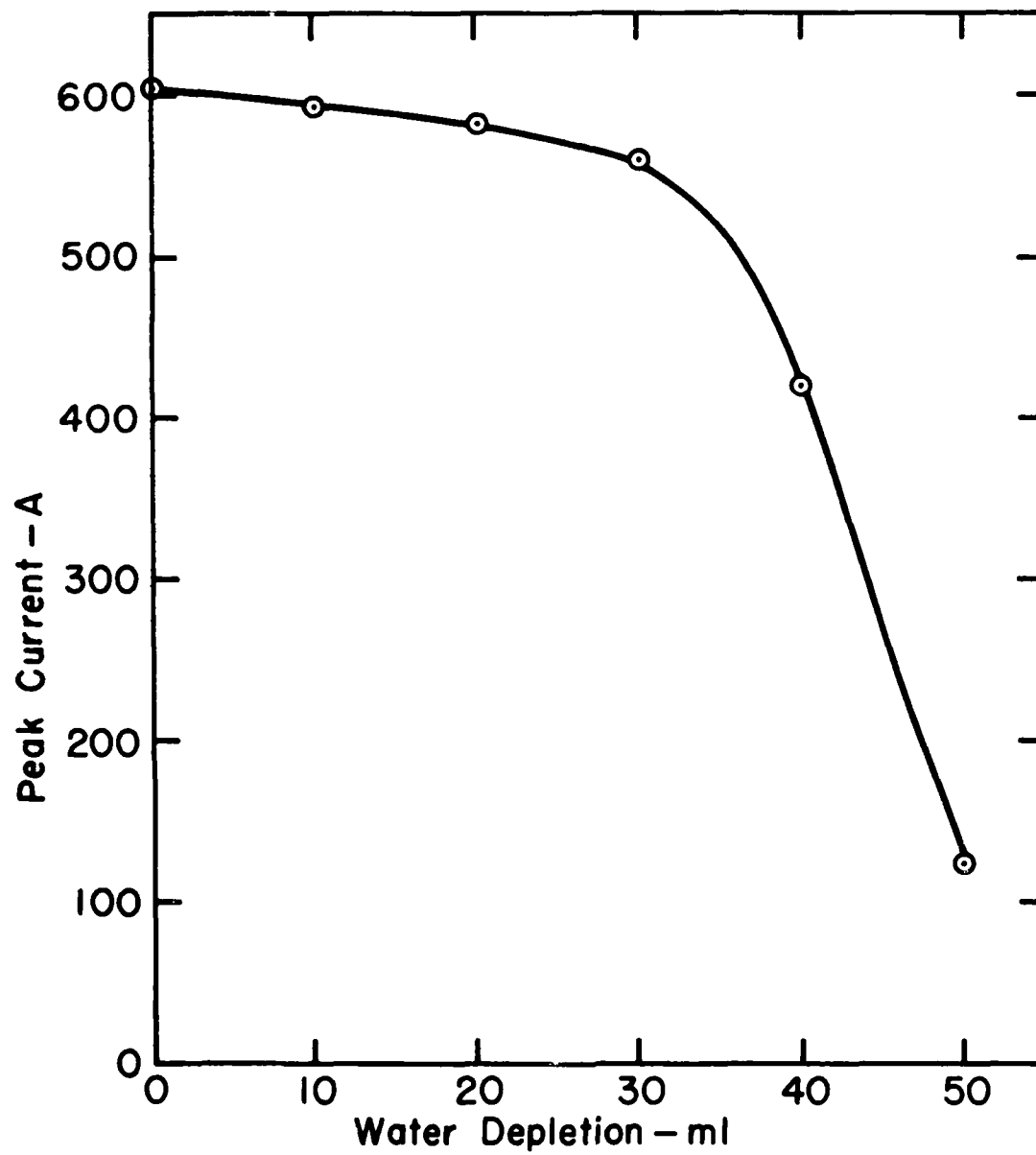
Fig. 1: Effect of Water Depletion on Peak Current.
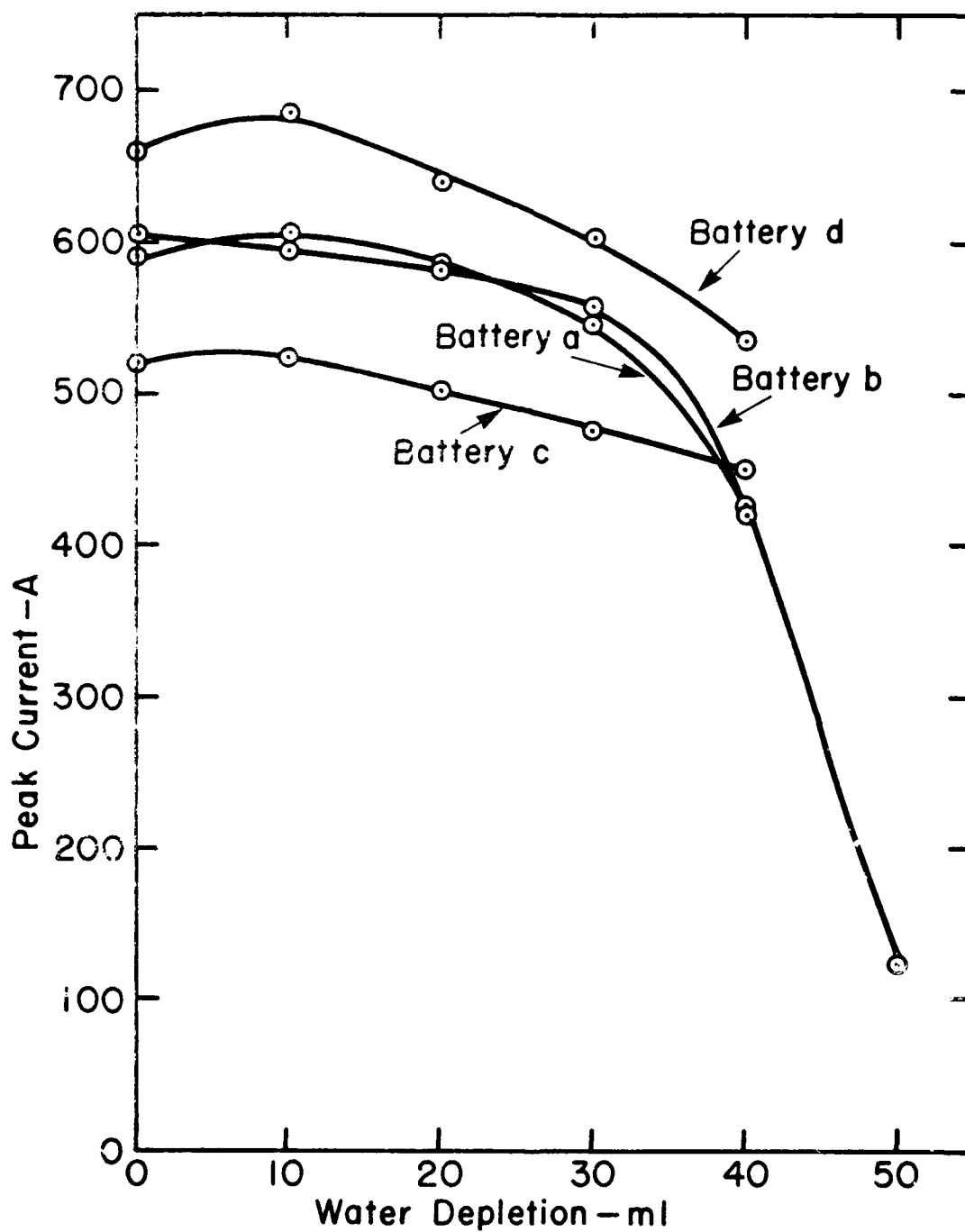*Battery (b), Room Temperature.*

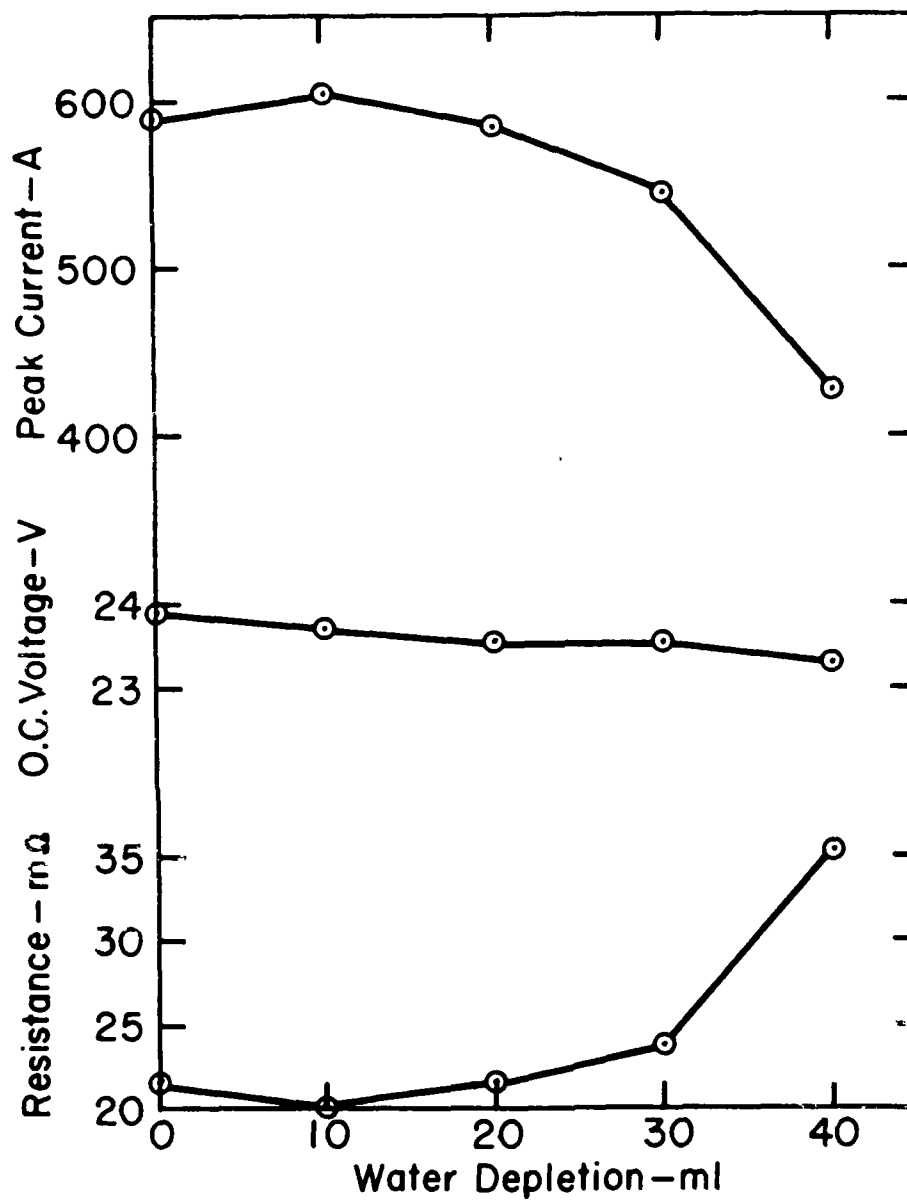*Fig. 2: Performances of Four 22 Ah Batteries at Room Temperature.*

Fig. 3: Effects of Water Depletion on Current, Voltage and Resistance of Battery (a).

of the cell direct increases in resistance may occur as a result of the pre-
sence of an insufficient amount of electrolyte. Both of these may result in
a change in current distribution in the cell to increase the proportion of
current flowing through longer path lengths.

Experiments were carried out to confirm that the change in perfor-
mance resulted from the water depletion and was not merely co-incident with
it. See Appendix IV.

WATER DEPLETION AND BATTERY CONDITION

During the tests in the laboratory, water depletion was frequently
carried considerably beyond the maximum recommended for field use. At the
end of each series, cell condition was examined to see whether any permanent
damage had been done and what maintenance procedures might be required. In
general, no damage was apparent during the relatively short investigation,
but the need for reconditioning was evident. Cell resistances were found to
be quite high and capacities to the one-volt end point were very low.
However, capacity to the zero volt endpoint was only slightly below normal.

It was also noted that when the one-volt endpoint was reached, if
water was added to the cell, the voltage immediately rose above one volt.
Considerably more capacity was then available before the one-volt endpoint
was reached a second time. Typical results are shown in Table I. Cell A
is discharged in the normal manner after severe water depletion. Cell B in
a similar state is discharged to 1 volt, then water is added and discharge
is continued.

As may be seen in the table, the cell resistances were several times
the normal value. Such severe depletion would not normally be expected in
the field so the deterioration should also not be so extreme. However, it
seems advisable that batteries which show very low electrolyte level, or have
given poor performance, should be checked for abnormally high cell resistances
before cycling in the battery shop. Water should be added to such cells until
the resistance approaches the normal value for the discharged state. If the
minimum necessary amount of water is used, it should be possible to avoid
overfilling. The normal "topping up" procedure could then be used at the
appropriate time to restore the fully normal state.

In the laboratory, when normal electrolyte levels were restored
and the battery was deep cycled once or twice, its normal performance was
restored.

TABLE I

Water Depletion Effects on Two Cells

	Normal	Water Severely Depleted	Difference
Cell A			
Resistance (milliohmmeter)	1.5 mΩ	5.4 mΩ	
Capacity to 1 V	24.7 Ah	7.0 Ah	17.7 Ah
Capacity to 0 V	26.1	20.5	5.6
Difference	1.4	13.5	
Cell B			
Resistance (milliohmmeter)	1.4 mΩ	6.0 mΩ	
Capacity to 1 V	21.9 Ah	3.9 Ah	18.0 Ah
Capacity to 1 V (water added)		18.1	3.8
Capacity to 0 V	22.5	20.4	2.1
Difference	0.6	2.3	

WATER DEPLETION EFFECTS AT DIFFERENT TEMPERATURES

A portion of the resistance of a cell is due to the resistance of the electrolyte through which the ionic current must flow. At room temperature the resistivity of the electrolyte is reasonably low so this component of the total cell resistance is also low. As the temperature of the cell is reduced the resistance of the metallic part of the current path falls slowly. However, the resistivity of the electrolyte increases rapidly to give a net increase in the total resistance of the cell. This means that the high rate performance decreases as the temperature drops. Water depletion effects are a complicating factor in this process.

To investigate the effects, the cranking tests were carried out at several different temperatures. Figure 4 shows typical results obtained with battery (a). It is seen that the decrease in performance as water is significantly depleted, applies to all temperatures. The shape of the curve is somewhat different, however, at -40°C. This is discussed in a later section.

It is seen also that, although, in general, performance decreases as the temperature falls below room temperature, it also decreases slightly as the temperature is raised to 40°C. Presumably this is due to the fact that the decrease in voltage at the increased temperature has a slightly greater effect than the relatively small decrease in electrolyte resistance at such temperatures.

WATER DEPLETION AND INITIAL ELECTROLYTE CONCENTRATION

In the experiments discussed above, the initial electrolyte concentration was approximately 30% KOH by weight. As water was depleted, performance deteriorated because of increased cell resistance. Since it was surmised that the resistivity change in the electrolyte played a part in the process, the matter was pursued further. A series of experiments were carried out in a manner similar to those already described, except that the initial KOH concentration in the batteries was adjusted to 20% instead of 30%. This concentration was chosen as a likely lower limit for the needed investigation.
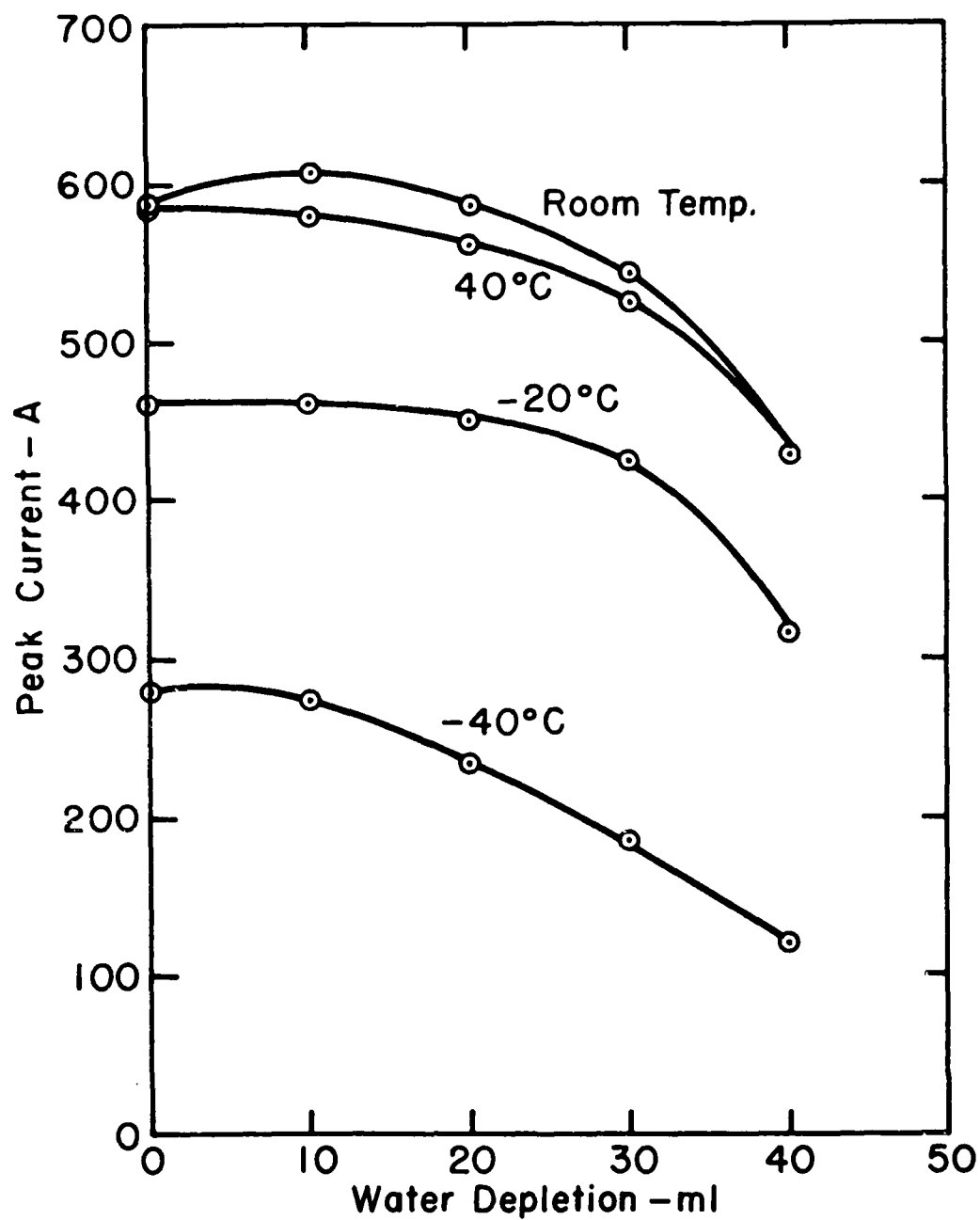
Fig. 4:   Effects of Water Depletion on Battery (a) at Different
Temperatures.

Figure 5 shows the results obtained with battery (a). The curves previously given for this battery with 30% KOH are included for comparison. It is seen that performance over the whole depletion range, at room temperature and at -20°C, was better than when the initial concentration was 30%. The results at -40°C differ considerably from those at the higher temperatures and are discussed in detail below. However, it is convenient to consider the general results first.

Figure 6 shows the resistivities of KOH electrolyte at three different temperatures over a range of concentrations (4). Because the electrolyte in nickel/cadmium batteries invariably contains some carbonate contamination, curves are given for electrolytes containing 1% and 5% carbonate.

It is seen that the resistivity of electrolyte with the higher carbonate concentration is slightly higher than that of the other concentration at room temperature, and the difference increases as the temperature drops. Also the resistivity in general increases significantly as the temperature drops below 0°C. In addition the resistivity decreases slightly as the KOH concentration changes from 20% to about 25% and then starts to increase again. Furthermore, the increase becomes very rapid, especially, for example, at 30% KOH with 5% carbonate at -20°C.

Figure 7 shows the resulting KOH concentration in a 22 Ah cell (assuming 100 ml of electrolyte) as water is depleted, for initial concentrations of 20% and 30%. It may be seen that for the former, after 30 ml of water depletion, the resulting concentration is about 27%, while for an initial concentration of 30%, it is about 40%. Returning to Figure 6, it may be seen that for an initial concentration of 20% KOH, the resistivity remains at a relatively low value throughout the depletion range. For the initial concentration of 30%, even before any depletion, the resistivity is already higher at low temperatures with a normal amount of carbonate present. As depletion continues, the resistivity increases still further.

The curves for -40°C in Figure 5 show the effect of a new factor, the formation of solids in the electrolyte. It is seen that starting with 20% KOH electrolyte at that temperature, cranking performance improved steadily and significantly as water was depleted for almost the first 30 ml. After this it started to fall in the normal manner. It is noteworthy that from the point where about 20 ml of water had been depleted, performance was again superior to that obtained when the initial electrolyte concentration was 30%.

The explanation for this behaviour is obvious from Figure 8, which shows a reproduction of the KOH liquidus curve (5) adjusted to include the effect of a few percent of carbonate contamination. At temperature-concentration points which lie "inside" the liquidus curve, the solution is completely liquid. At points to the left of the curve ice is present. This increases the concentration of the remaining liquid to the point where, at the given temperature, the point lies on the curve and no further freezing takes place. Similarly for temperature-concentration points to the right of the enclosed area, some of the KOH comes out of solution to form solid particles of hydrated forms of KOH. This reduces the concentration of the remaining liquid, again until the point for the given temperature lies on the curve and no further precipitation takes place.
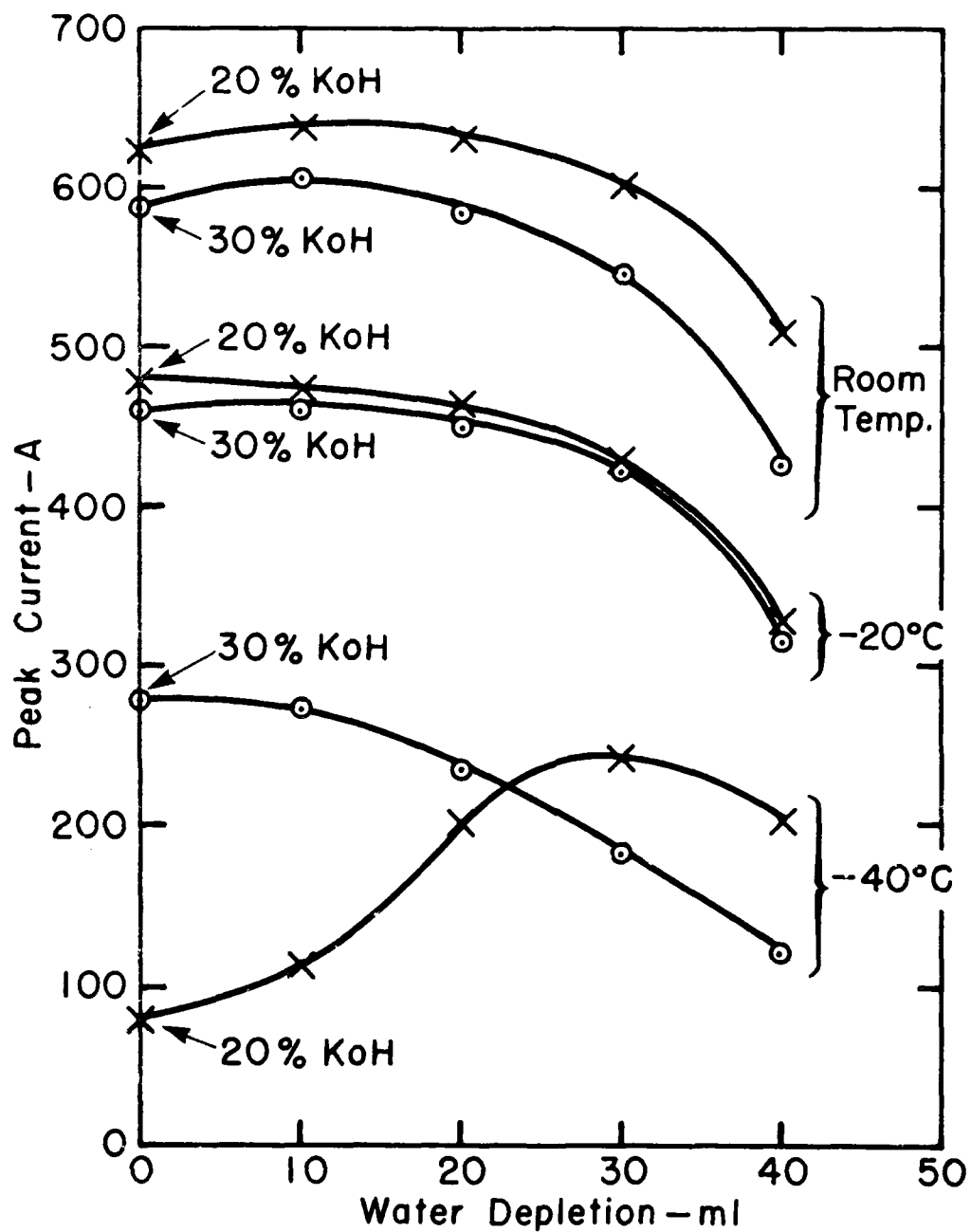
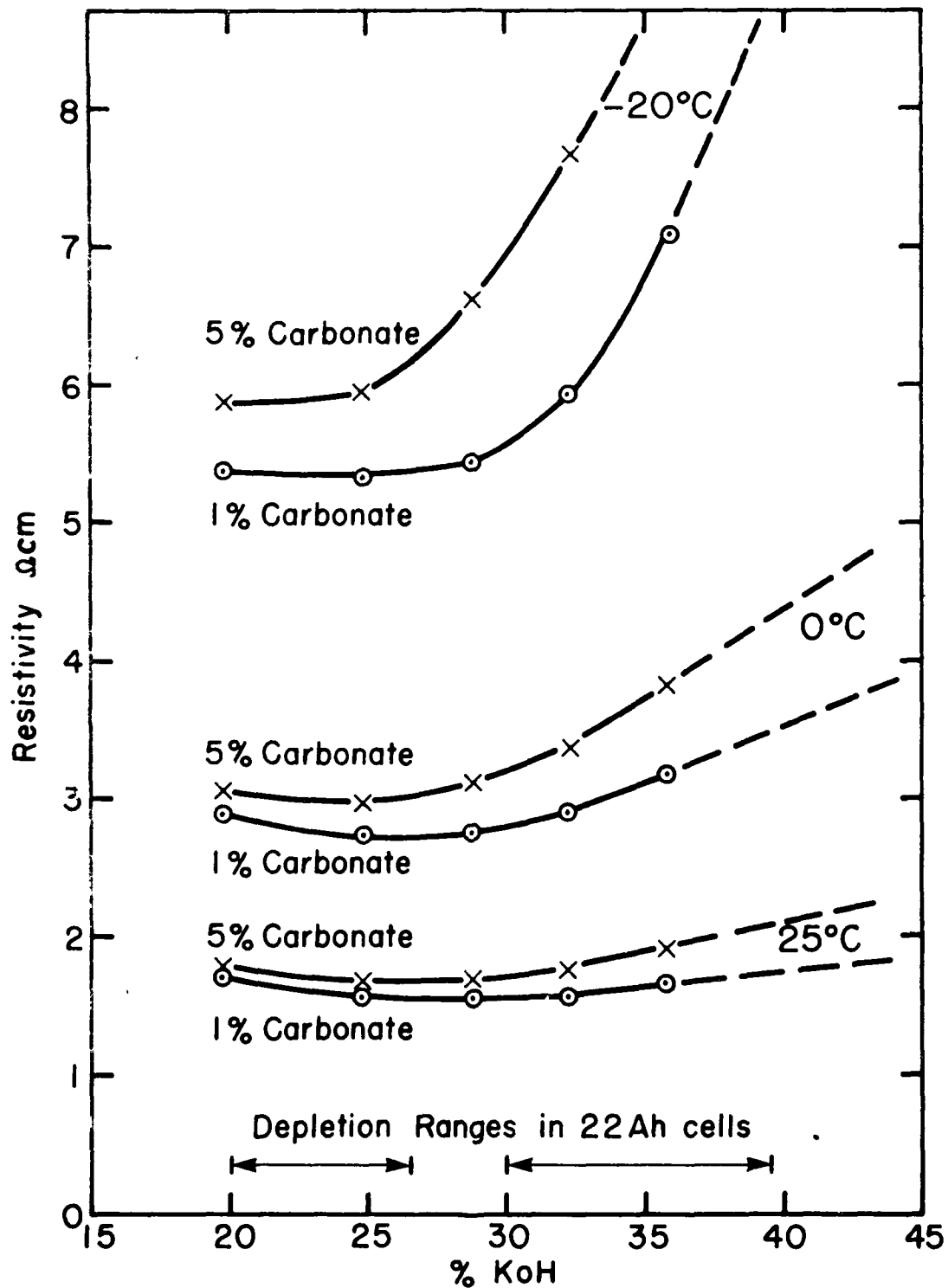Fig. 5: *Effects of KOH Concentration on Peak Current - Battery (a).*

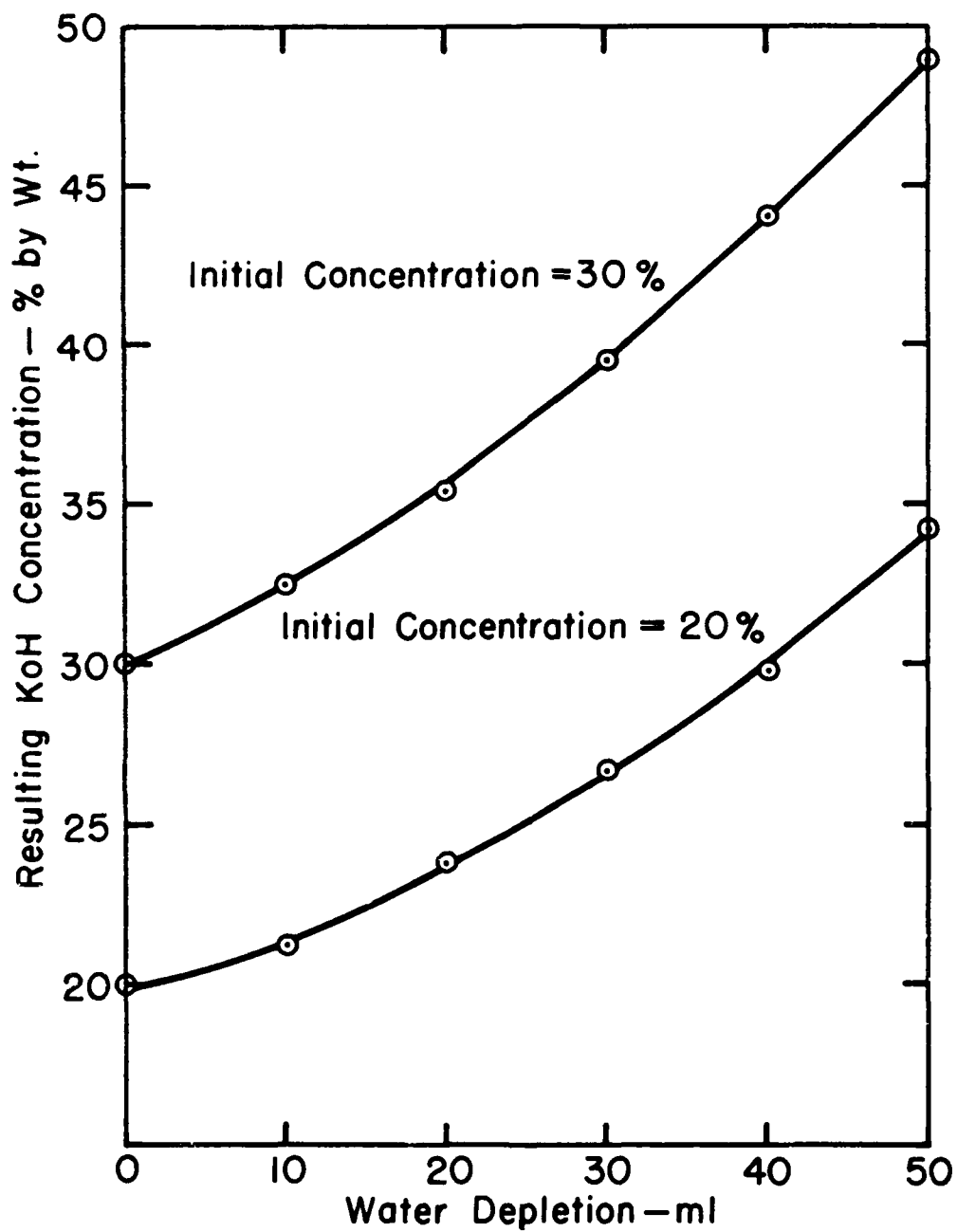*Fig. 6: Effect of KOH Concentration on Electrolyte Resistivity.*

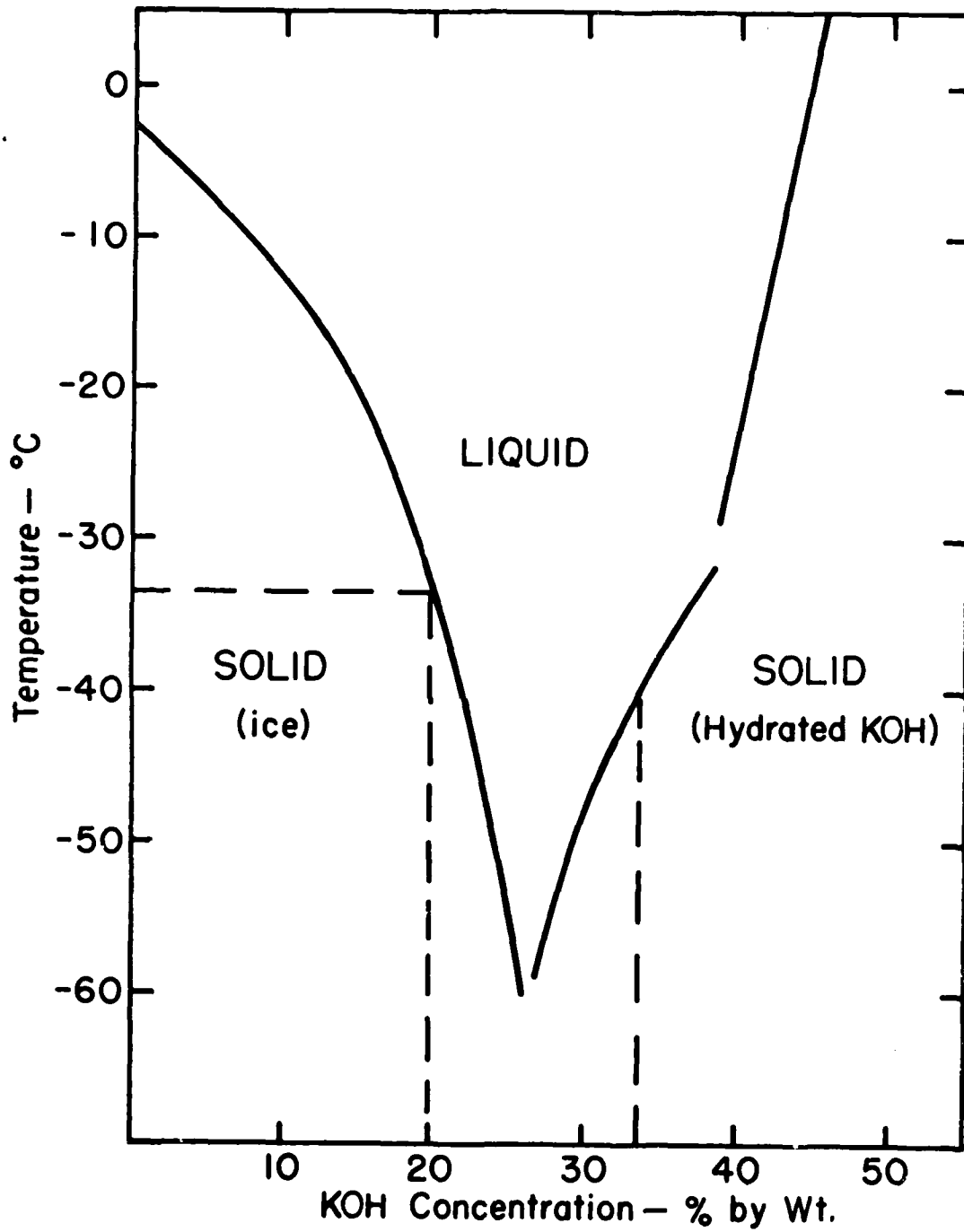*Fig. 7: Water Depletion Effect on KOH Concentration in a 22 Ah Cell.*

Fig. 8: Liquidus Curve - KOH with 5% Carbonate.

In either case, the presence of solid material in the electrolyte increases the resistance of the cell. It now becomes clear, at least qualitatively, why the cranking capability at -40°C behaved as shown in Figure 5. When the initial KOH concentration was 20%, the presence of ice in the cell increased its resistance. As water depletion increased the KOH concentration, the amount of ice was reduced, thus decreasing the resistance and improving performance. In the case where the initial KOH concentration was 30%, only a small amount of water depletion was necessary to bring the electrolyte to the point where solid KOH (hydrated) started to form. This process continued to increase the cell resistance and resulted in performance falling more rapidly than with the same depletion at higher temperatures.

The above results seem to indicate that when water depletion is taken into account, 30% initial KOH concentration is too high under all temperature conditions. An initial concentration of 20% is satisfactory at temperatures no lower than -20°C. Some intermediate value should be satisfactory to -40°C. A single test at -40°C with 25% KOH concentration gave a peak current 14% higher than the same battery with 30% KOH concentration.

WATER DEPLETION AND GAS ENTRAPMENT

Gas entrapment in the plate packs of some batteries has been observed in the laboratory and in at least one case in a battery shop (6). It is not known whether vibration, for example, in the aircraft environment has any effect on the ease with which gas, formed during overcharge, escapes from the tightly packed plate pack. However, some of the batteries in this study showed significant increases in resistance as a result of gas entrapment. In the worst case, application of a vacuum to the vents of the cells between the two high rate discharges increased the subsequent peak current by approximately 15%.

It was noted that the tendency to trap gas decreased slightly as more and more water was depleted. Presumably the lowering of the electrolyte level facilitated the escape of bubbles of gas. Also there was a slight reduction in gas entrapped when the initial KOH concentration was reduced to 20%.

Aside from the above effect on performance, the gas entrapment is significant in that it directly reduces the maximum amount of electrolyte which may (initially) be present in the cell without "spewing" or overflowing. This, of course, limits the amount of water which may be depleted before the electrolyte level reaches its allowable minimum and maintenance becomes necessary. It also seems desirable that "topping up" procedures should give the maximum electrolyte level without danger of overflow due to active gassing and entrapped gas. This is most conveniently done by filling to a pre-determined level while the fully charged battery continues to be charged at a current representative of the normal float current.

EVAPORATION LOSSES

A brief experiment was carried out to investigate the extent to which water losses in a battery may be due to evaporation. Battery (d), in fully charged condition, was used. Each cell was weighed and then the battery was kept on open circuit for a period of approximately 114 hours at an ambient temperature of 40°C. The fan in the chamber continuously directed an air-stream over the tops of the cells. At the end of the period each cell was weighed again. It was found that on the average, each cell lost approximately 0.6 grams.

From this measurement and from observations during the course of other experiments in the investigation, it is concluded that evaporation probably accounts for about one percent of the water losses in a nickel/cadmium aircraft battery and is completely negligible. Elevated temperatures may lead to accelerated water loss but this is due to increased floating current during overcharge and not to evaporation. This is discussed in the next section.

BATTERY TEMPERATURE AND WATER DEPLETION RATE

Water depletion results almost entirely from the electrolysis during overcharge. The rate of depletion therefore depends directly on the magnitude and duration of the "float" current while on overcharge. For a given fixed charging voltage the float current is very low at low temperatures and in-creases rapidly with increasing temperature above about 20°C. Precise values vary from battery to battery and with the actual conditions. However, for illustrative purposes, the measurements on battery (b) are given in Figure 9. The battery was charged at a fixed voltage of 28.5 volts while in a temper-ature chamber at the ambients indicated. Also given in the Figure is a curve showing the corresponding water depletion in 25 flights of $2\frac{1}{2}$ hours each (with arbitrary assumptions regarding the rapidity of recharge prior to the start of overcharge, etc.). It is seen that at low temperatures very little depletion takes place. At 40°C, the depletion in 25 flights slightly exceeds the recommended maximum of 30 ml per cell.

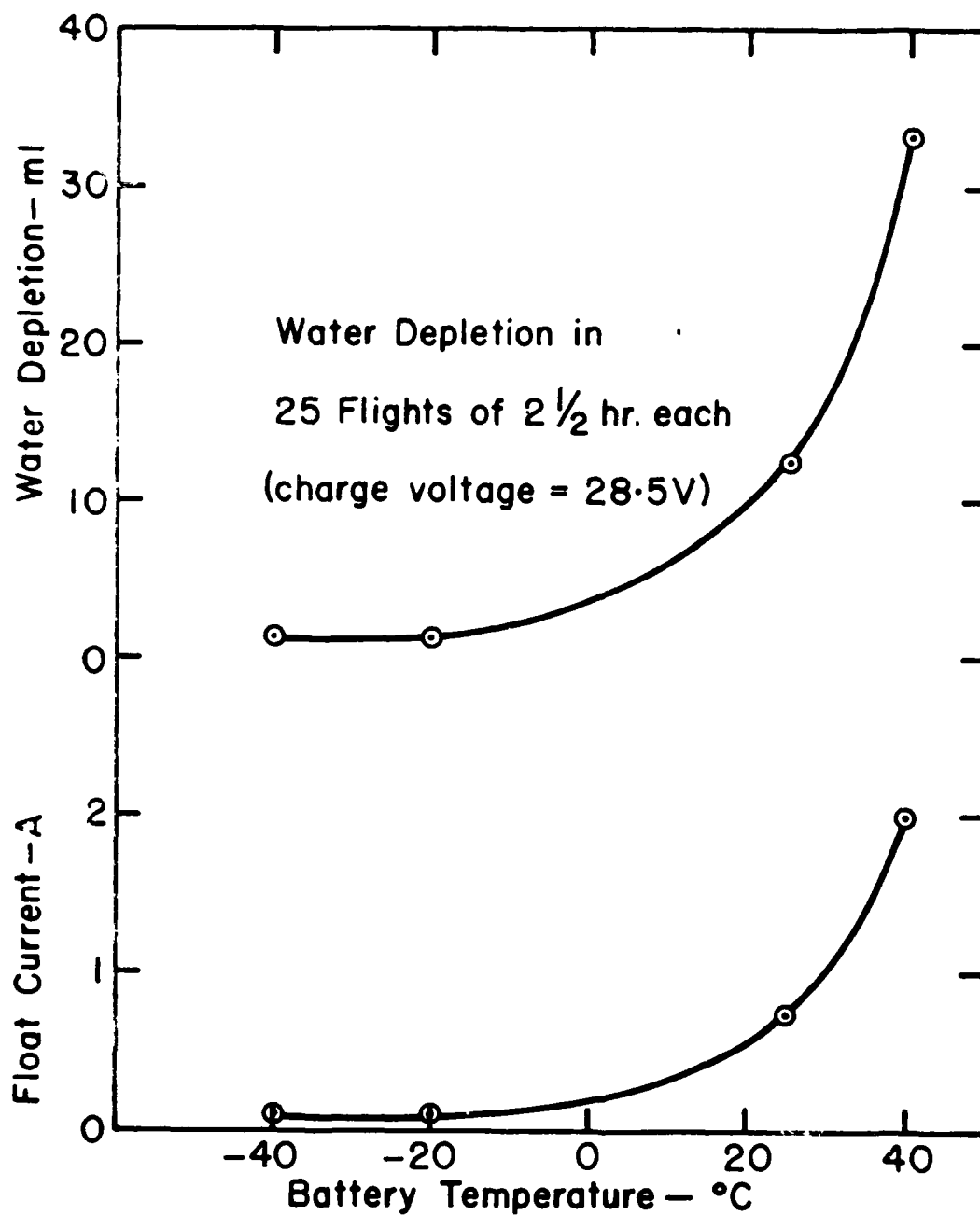*Fig. 9: Battery Temperature Effects on Float Current and Water Loss, Battery (b).*

In practice, the conditions may differ considerably from those assumed in the above illustration. Praticularly if the battery is frequently used for engine cranking, its temperature will not be uniform over the whole battery, nor is it likely to remain constant throughout each flight. Field experience in each set of conditions is therefore necessary to determine the actual average rate of water depletion and the corresponding need for maintenance.

Further insight into water depletion rates is gained from observations of the magnitudes of the floating current during a test on the effects of engine cranking at frequent intervals (described in a later section). Figure 10 shows the floating current for battery (c), but in this case the temperature range is extended, and values above 40°C relate to the maximum "hot spot" measured between the cells during the cranking experiment. The float current exceeded 10A at the end of the series. Thus it is seen that under some conditions, such as hot summer operations or frequent cranking, for example, much higher water depletion rates than those shown in Figure 9 could be experienced. It should also be noted that high discharge rates heat a battery up quickly but significant cooling rates occur only if the battery is exposed to very low temperature ambients (7).

CRANKING AT HALF-HOUR INTERVALS

This portion of the investigation was undertaken to determine which factor or factors impose a limit on the number of times per day a battery may be used for engine cranking, with intervening recharges. The tests were carried out as follows, with batteries (a) and (c):

(i)   The battery, in good condition, was placed in a confined area (a temperature chamber with the door partly open and no heating or cooling switched on) as it might be in a battery compartment. The temperature surrounding the battery increased considerably during the tests. The battery lid was left off to permit the use of many thermocouples, voltage measurement connections and tubing to cell vents. The thermocouples were inserted between cells at various locations and depths.

(ii)   Two fifteen second discharges into a 20 mΩ load were made, one minute apart. A vacuum was connected to the cell vents between the discharges to study gas entrapment effects, if any.

(iii)   After the discharges the battery was recharged for 20 minutes at a voltage of 28.5V with a current limit of 80A.

(iv)   A 10 minute open circuit stand was allowed after the recharge. The complete cycle was then repeated. Thus a double high rate discharge was carried out every half-hour until the series was terminated because battery
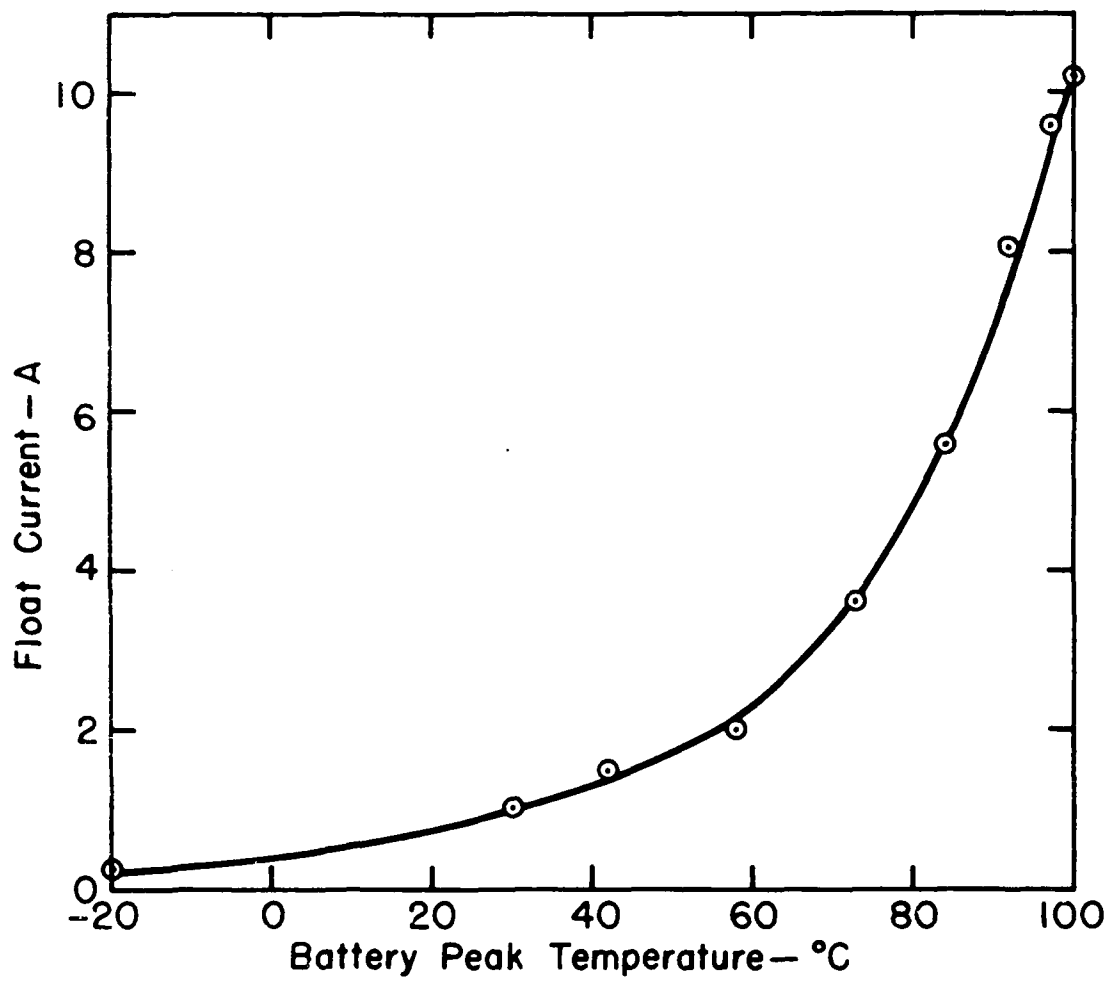
Fig. 10: Effect of High Temperatures on Float Current, Battery (c).

temperature was considered to be approaching the boiling point of the electrolyte. Two such series of tests, on different days, were carried out with each battery.

As expected, considerable heating took place during each pair of discharges and only a portion of this heat escaped before the next cycle. Also, slight heating took place during each recharge period (7). Thus the battery temperature rose to a higher value with each cycle.

At times, during the cycles at elevated temperatures there were mild but not persistent indications of approaching thermal runaway. In such cases, after a relatively small increase in charging current, the rate became constant again.

Cycles were continued until the highest temperature between cells reached the vicinity of 100°C. Under the laboratory conditions the above temperature was reached in 10 to 12 "double engine start" cycles. Throughout this period cranking performance remained relatively constant, with a very slight decrease in peak current as the battery voltage decreased slightly at the higher temperatures. To some extent this voltage decrease was counteracted by the voltage increase resulting from the previous charge only ten minutes earlier.

There was no significant change in battery resistance over the temperature range (i.e. from room temperature to about 100°C). In the case of battery (c), which normally traps a significant amount of gas, the effects were present throughout the temperature range.

After each series, each battery was allowed to cool to room temperature and was discharged. No change in capacity or other performance characteristics was observed. However, there was a slight increase in carbonate concentration. It would seem possible that this was due to deterioration of nylon in the separator. More extensive investigation would be needed to determine whether this is so, how serious the consequences would be, and whether replacement of the nylon with a material capable of withstanding higher temperatures would be warranted.

Thus the above experiments seem to indicate the following:

(a)   Repeated cranking at intervals which permit the battery to be recharged, seem possible until "hot spot" battery temperatures reach about 100°C.

(b)   Danger of thermal runaway during the recharge period may be present but does not seem serious with healthy cells. Runaway would occur if heat generated during charging periods exceeded the cooling rate of the battery (8). These depend largely, of course, on the charging voltage and on the cooling environment of the battery. The cooling rate and the charging rate both increase as the battery temperature increases. It seems likely that if conditions did lead to thermal runaway, but if charging was interrupted before the electrolyte started to boil, no serious harm would result.

(c)   It would, of course, seem prudent to exercise caution in the field in doing repetative cycles of engine cranking until experience showed that field conditions did in fact give the same behaviour as laboratory conditions,

and that long term deleterious effects did not appear.

(d)   As pointed out previously, floating currents become very high at
high battery temperatures (10A to 12A were observed during the tests described
above). This implies more rapid water depletion and possibly more active
circulation of debris within the cell.

(e)   Battery configurations and installations which promote more rapid
cooling would extend "frequent cranking" capabilities.

(f)   Ability of the nylon to withstand frequent excursions to such high
temperatures requires further investigation.

LOW TEMPERATURE OPERATION

        As discussed previously, performance of nickel/cadmium aircraft
batteries is reduced at low temperatures due to the increased electrolyte
resistivity. In an attempt to warm the battery slightly, it is common
practice to carry out one or more moderate discharges prior to attempting
engine cranking at low temperature. Limited data on this procedure were ob-
tained during the current study.

        The 4 Ah discharges at 10A which preceded the cranking tests des-
cribed earlier, marginally raised the battery temperature, and at low ambient
temperatures, gave slightly improved cranking performance. As one example,
battery (a) which at -20°C gave a peak current of 447A if the 10A discharge
was omitted, gave 460A when it was included. However, this does not reflect
the observed reduction of the battery resistance from 37 mΩ to 31 mΩ, which by
itself should give a much greater increase. The failure to do so results from
the reduction in battery voltage which accompanies the 10A discharge.

        Since during a discharge, the higher the current drawn, the larger
is the fraction of the total energy which is dissipated as heat within the
cell, an attempt was made to test the efficacy of this approach to get im-
proved performance. Starting with battery (a) at -40°C, a sequence of dis-
charges of a few seconds each, were carried out into a 20 mΩ load at 2 minute
intervals.

        The results are shown in Figure 11. The battery temperature in-
creased to about -20°C after about half a dozen discharges. However, the
resistance dropped more slowly than would be expected, presumably due to the
effects of the relatively high rate discharges. Consequently, the current did
not increase as rapidly as would otherwise be the case. By the time the
battery reached -20°C the current had reached about 350A which is about 100A
less that obtained from the same battery at that temperature under normal

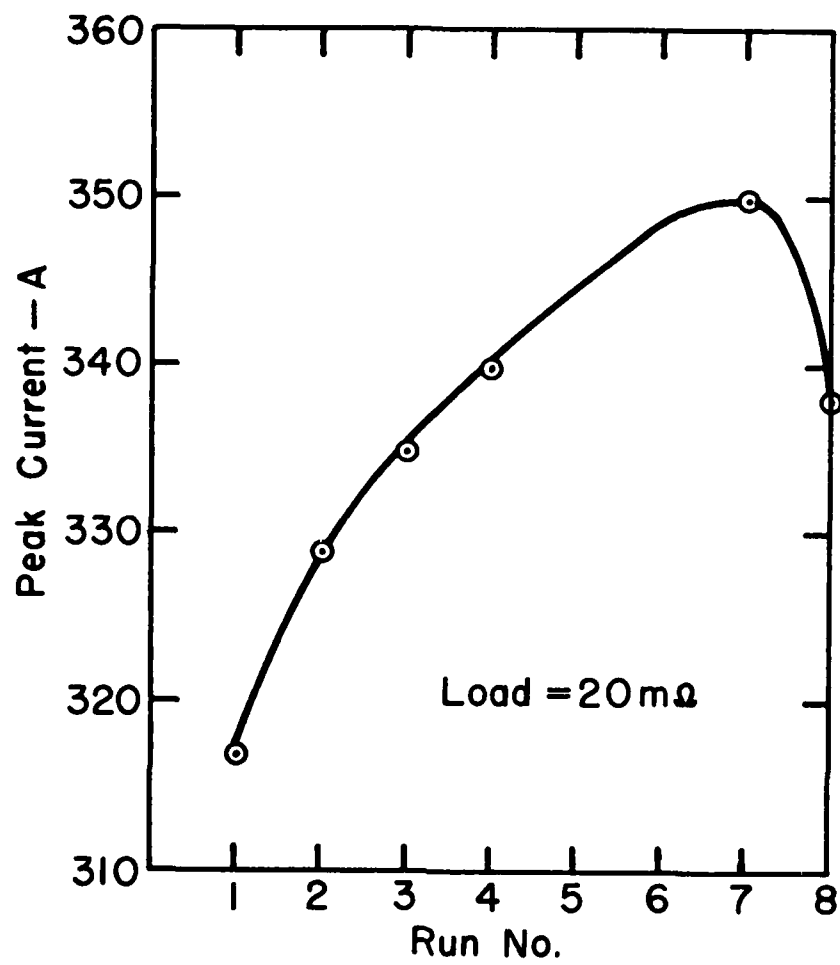*Fig. 11: Effect of Warming Battery (a) by Repeated Discharges.
Initial Battery Temperature: -40°C.*

conditions. Furthermore, continuing the discharges beyond this point no longer had the desired effect. Presumably, passivation of the plates and/or the state of remaining charge had reached the point of counteracting further increases in temperature.

Subsequent discharge of the battery at room temperature gave poor capacity and deep discharges were necessary to recondition the battery.

It is reasonable to expect that attempts to optimize the size of the load and the choice of interval between successive discharges would yield improvement in this approach to low temperature cranking. However, no attempt has been made to investigate the matter further.

CONCLUSIONS

This laboratory investigation on the use of Celgard nickel/cadmium aircraft batteries with emphasis on the turbine engine cranking capability leads to the following conclusions:

1.   Use of nickel/cadmium batteries with Celgard barriers in cranking turbine engines does not seem to harm the batteries or directly lead to any dangerous conditions.

2.   Water depletion during overcharge eventually reduces cranking capability. Replacement of the water and one or two deep cycles restore original performance.

3.   Repeated high rate discharges, with intervening recharges, during a period of a few hours, such as engine cranking at half hour intervals for example, results in steadily increasing battery temperatures. The temperatures would normally not be uniformly distributed throughout the battery, depending on the cooling configuration. However, no immediate deleterious effects have been observed as long as the hottest locations remain below about 100°C. Performance decreased only slightly with increasing temperatures. Although short term trends towards thermal runaway were sometimes observed, these did not persist in the batteries tested. A slight increase in carbonate concentration in the electrolyte may be evidence of nylon degradation.

4.   Since low electrolyte level is the determining factor in setting maintenance intervals, there is an advantage in starting with a maximum level. Because of variation in gas entrapment characteristics, it would probably be expedient to "top up" cells to an established limit while charging the fully charged battery at a "floating current" slightly in excess of that expected in the aircraft. Floating current in the aircraft using constant voltage charging systems depends largely on the bus voltage and maximum battery temperature expected.

5.   Aircraft charging voltage set at the minimum which will adequately charge the battery, minimizes the rate of water depletion.

6.   Initial electrolyte concentration (i.e. concentration before water depletion by overcharge) for very low temperatures should be such that neither ice nor solid hydrated KOH forms in the battery during the service period, i.e. over the expected water depletion range. This would appear to be in the region of about 25% to 27% KOH by weight, assuming low carbonate content. For temperatures above -20°C a concentration as low as 20% seems adequate.

7.   Batteries should be deep cycled in the battery shop on a regular basis. Attainment of nominal capacity is not an adequate indication of plate health.

It should be noted that the above conclusions are based on laboratory investigations. It is possible that field conditions may alter some factors, and that long term effects exist which were not observed in the accelerated laboratory procedures.

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APPENDIX I

BATTERIES USED

A broad base to ensure general applicability of the observations was obtained by using several batteries, each with a different history and with variations in constructional details. However, they all provided approximately the same amount of "headroom" for electrolyte. No "low maintenance" cells were included.

A brief description of each battery is given below.

(a)   A new 22 Ah 19 cell battery with separators of nylon-Celgard 3400-nylon and medium rate 17 plate cells, obtained from a commercial manufacturer.

(b)   A 22 Ah 19 cell battery, commercially rebuilt with nylon-Celgard 3401-nylon separators in used 25 plate cells. After rebuilding, the battery had been subjected to extensive and rigorous tests in our laboratory for three years prior to this investigation. After the equivalent of about two years of normal aircraft service in the current tests, and during simulation of service in an ambient of 40°C, one of the cells failed. Several other cells were judged to be nearing failure. Tests on this battery were therefore discontinued, but the data obtained prior to the failure are included and were not significantly different from the others.

(c)   A 22 Ah 19 cell battery made of old 17 plate cells and rebuilt in the laboratory with nylon-Celgard 3400-nylon separators. This battery had been subjected to about six months of rigorous testing before its inclusion in this investigation.

(d)   A 22 Ah 19 cell battery with 25 plate cells which had been commercially rebuilt and was used for some time in the field. Due to cell leakages it was subsequently removed from service and turned over to the laboratory. There it was rebuilt again using nylon-Celgard 3500-nylon in about half of the cells and nylon-Permion 2291-nylon in the others. The tests on this battery were the only ones in the current series involving either Celgard 3500 or Permion 2291. At normal temperatures, behaviour of this battery was not significantly different from the rest. However, at low temperatures the cells with Permion did not function satisfactorily. See Appendix III.

(e)   A new 36 Ah 20 cell battery with Celgard 3400 obtained from a commercial manufacturer.

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(f)   A new 36 Ah 20 cell battery similar to (e) above, from the same
manufacturer but built with cellophane instead of Celgard. This was the
only battery with cellophane in the study.

The tests on the two 36 Ah batteries were brief and differed
slightly from the tests on the 22 Ah batteries since the temperature chamber
used in the study was not large enough to permit the normal connections to be
made to these larger batteries. For this reason the chamber door was opened
during tests and other associated changes in procedure were followed. See
Appendix II.

Many of the tests on the 22 Ah batteries were repeated with
different initial concentrations of electrolyte. The basic investigation was
done with customary 30% concentration of potassium hydroxide (KOH), by weight.
Considerable work was also done with an initial concentration of 20%, and a
few tests were carried out with 25% KOH. Carbonate concentrations were
generally about 2 or 3%, but were slightly higher in the battery with
cellophane.

APPENDIX II

TESTS ON 36 Ah BATTERIES

As indicated previously, the tests carried on these two 20 cell 36 Ah batteries were more limited as a result of equipment difficulties, and it was felt unnecessary to pursue the matter further. The work done indicated that the general behaviour of the larger battery with Celgard was similar to that of the 22 Ah batteries. However, the early work done with the battery built with cellophane (battery (f)) gave confusing results. It was later established that the rates of water depletion for a given number of ampere hours of overcharge varied so widely from cell to cell (from nearly the theoretical maximum to nearly zero) as to render the results meaningless. Since batteries with cellophane barriers are in any case regarded as unsuitable for the cranking application, no further work was done with this battery.

The electrolyte concentration in the battery with Celgard (battery (e)) was left as received and varied from about 27% to over 29% with less than 2% carbonate. The performance as water was depleted is shown in Figure 12. From the curve for room temperature operation it would appear that depletion up to about 40 ml of water would be possible (the manufacturer gives a limit of 30 ml). At -20°C the cranking performance deteriorated at a more rapid rate than at room temperature. This is unlike the behaviour of the 22 Ah batteries and the reason for it is unknown. However, if a decrease of about 10% in performance is acceptable, the same 40 ml depletion limit would still apply.

The length of service which would result in water depletion of the above amount, again depends on the circumstances of the application.
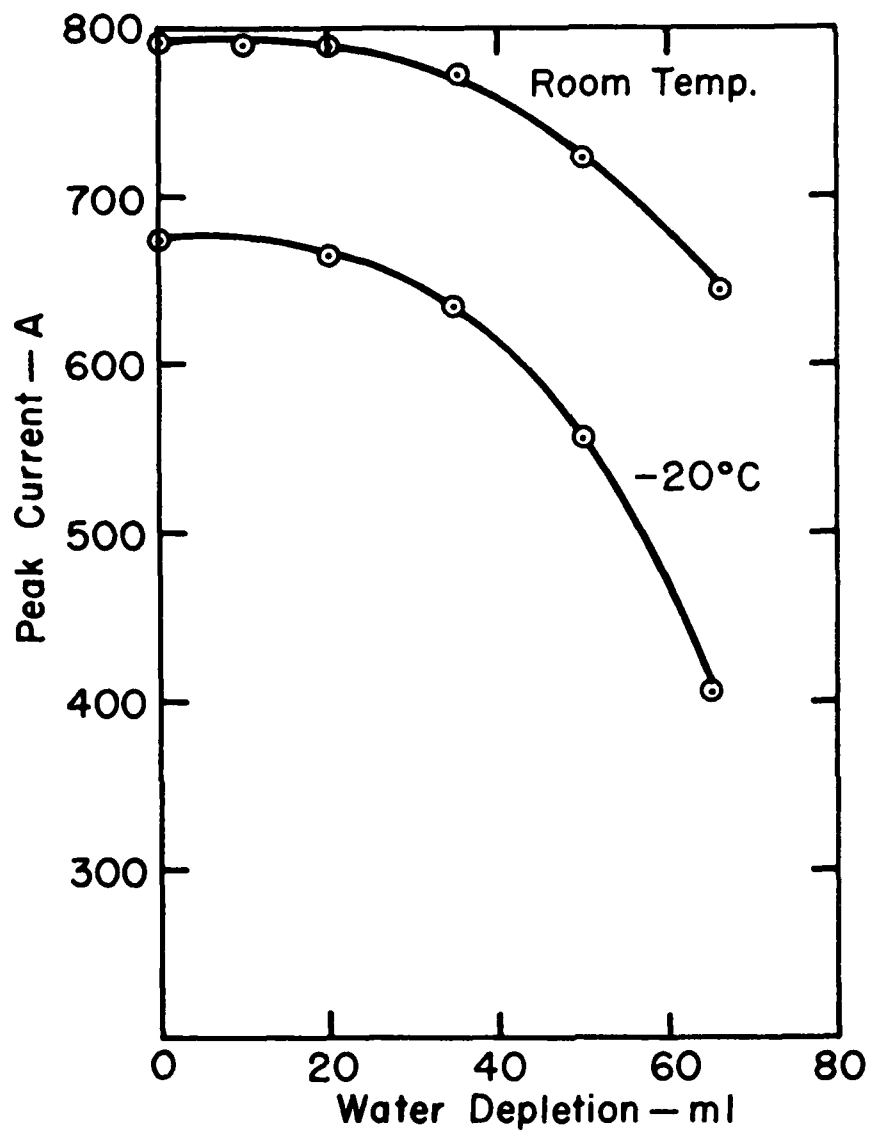
Fig. 12: Water Depletion Effect on 36 Ah Battery (e).

APPENDIX III

PERMION AND CELGARD 3500

As another method of broadening the base of the investigations reported in this paper, one battery was made up of cells rebuilt with the above barrier materials. Nine cells were made with Permion 2291 40/20, and ten with Celgard 3500. The latter has a larger pore size than the Celgard 3400 series.

This battery confirmed the general observations made in the body of the paper. In addition, however, the following was noted. At low temperatures the resistance of the cells with Permion rose significantly higher than that of the cells with Celgard.

At room temperature the resistance of the electrolyte and separator materials is very low and differences between the materials cannot readily be determined by resistance measurements. At low temperatures these resistances increase greatly and form a significant portion of the total cell resistance. In the above battery considerable differences in resistance between the cells with the different barrier materials became evident at -20°C and below. Furthermore, a difference in behaviour during discharge became evident at -40°C. The voltage of the cells with Celgard decreased gradually during the 10 second discharge into a 20 mΩ load. The voltage of the cells with Permion behaved in the opposite manner.

Although the different behaviours attracted attention, it is doubtful as to whether any practical significance should be attached to the tendency for the voltage rise in the cells which Permion since the initial voltage was too low to be of use. Comparative measurements are shown in Table II, for a 10 second discharge into the 20 mΩ load. Peak current was 290A.

TABLE II

Comparative Measurements* for Cells with
Celgard 3500 and Permion 2291 at -40°C

KOH concentration: 30%
Load   : 20 mΩ

	Celgard	Permion
Initial Resistance :	2.69 mΩ	4.52 mΩ
Resistance after 10 sec. under load:	2.58 mΩ	3.69 mΩ
Initial voltage under load :	0.576 V	0.024 V
Final voltage under load :	0.400 V	0.135 V

* Average per cell.

APPENDIX IV

EXPERIMENTAL COUNTERCHECKS

To ensure that the reduction in cranking performance described above under "Water Depletion and Cranking Performance" was indeed caused by the water depletion and not merely coincident with it, additional experiments were carried out.

In one series the procedures in the original experiment at room temperature were repeated except that the water depletion steps were omitted. It was found that the peak current obtained did not decrease significantly as the tests progressed. In another series the procedures were repeated again except that the intervening discharges were omitted. A discharge was carried out only after the end of the last water depletion step. It was found that the peak current obtained was now very low and similar to the corresponding point in the original full series.

These results are shown in Figure 13. Curve 2 is a reproduction of the curve in Figure 1 and shows the normal deterioration of performance as water depletion progresses. Curve 1 shows that the deterioration does not take place if water in the electrolyte is not depleted. Curve 3 merely joins the initial performance to that obtained after all of depletion in the series is completed without other discharges. Thus it is confirmed that the depletion is the cause and not merely coincidental with the deterioration.
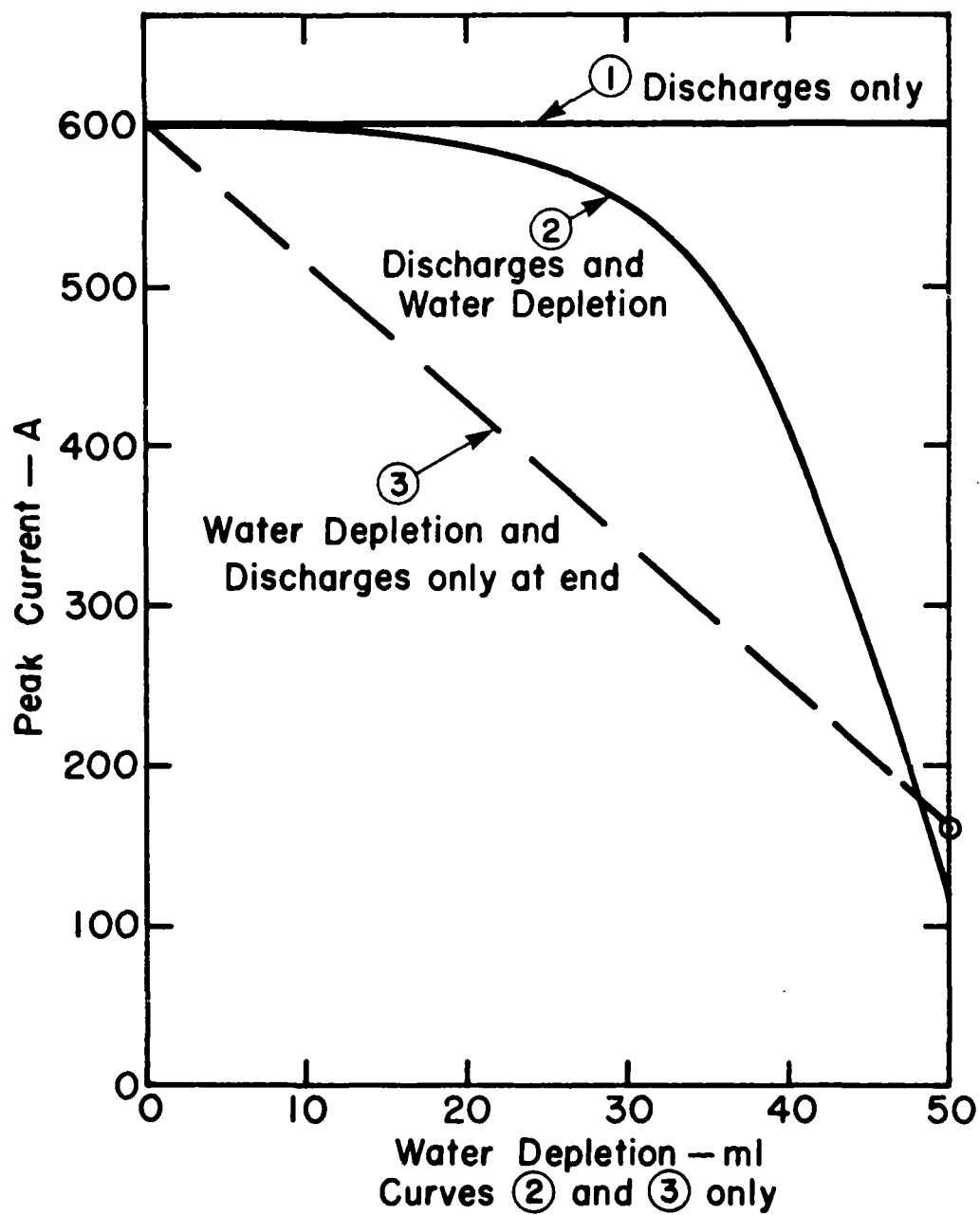
Fig. 13: Confirmation of Depletion Effect, Battery (c).

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Nickel/cadmium aircraft batteries with Celgard barrier materials may be freely used for cranking turbine engines. However, frequent use for this purpose with insufficient intervening cooling still results in successive increases in battery temperature. The experiments were terminated when "hot spot" temperatures between the cells reached 100°C. Short term experiments indicated no apparent problems.

In long term use for cranking, performance was found to deteriorate as water depletion, due to overcharge, became severe. Replacement of water and deep cycling restored the original condition.

Improved cranking performance was found with the initial electrolyte concentrations below the customary 30% potassium hydroxide.

It is emphasized that the above comments do not apply to batteries with cellophane barriers.

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KEY WORDS

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